CHAPTER 2

HYDROLOGY

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APPENDICES

2.1 Overview

2.1.1 Introduction

Estimation of the peak rate of runoff, volume of runoff, and time distribution of flow is fundamental to the design of drainage facilities. Errors in the estimation will result in a structure that is either undersized and causes drainage problems (e.g., flooding, safety, nuisance, etc.) or oversized and costs more than necessary. On the other hand, it must be realized that any hydrologic analysis is only an approximation. The relationship between the amount of precipitation on a drainage basin and the amount of runoff from the basin is complex. Too few data are available on the factors influencing the rural and urban rainfall-runoff relationship to expect exact solutions.

2.1.2 Factors Affecting Floods

In the hydrologic analysis for a drainage structure, there are many factors that affect floods. Some of the factors which need to be recognized and considered on a site-by-site basis are:

<u>Drainage Basin Characteristics</u>

- Size and Shape
- Slope
- Ground Cover and Land Use
- Geology
- Soil Types
- Surface Infiltration
- Ponding and Storage
- Watershed Development Potential

<u>Stream Channel Characteristics</u>

- Geometry and Configuration
- Natural Controls
- Artificial Controls
- Channel Modifications
- Agradation - Degradation
- Debris
- Manning's "n"
- Slope

<u>Floodplain Characteristics</u>

- Slope
- Vegetation
- Alignment
- Storage
- Location of Structures
- Obstructions to Flow

<u>Meteorological Characteristics</u>

- Time Rate and Amounts of Precipitation
- Historical Flood Heights

2.1.3 Hydrologic Method Selection

Many hydrologic methods have been developed and used in urban watersheds. Table 2-1 lists two recommended methods. Other methods may be used if they received prior approval from the Director of Public Works and Utility and if they are calibrated to local conditions and tested for accuracy and reliability. In addition, complete source documentation must be submitted for approval.

Methods listed in Table 2-1 have been selected for use in Lincoln, Nebraska based on several considerations, including the following:

- Verification of their accuracy in duplicating local hydrologic estimates of a range of design storms.
- Availability of equations, nomographs, and computer programs.
- Use and familiarity with the methods used by local municipalities and consulting engineers.

Table 2-1 Recommended Hydrologic Methods[1]

Method	Size Limitations[2]	Comments
Rational	0 - 150 Acres	Method can be used for estimating peak flows and the design of small subdivision-type storm drain systems. (Method shall not be used for design of storage facilities.)
SCS[3] Curve Number	0 - 2,000[4] Acres	Method can be used for estimating peak flows and hydrographs. Method shall be used for the design of all drainage structures and shall be used for design of any storage facility or any other facility with a drainage basin greater than 150 acres.

[1] The Lincoln Public Works and Utilities Department has selected the HEC-HMS computer program for stormwater master planning efforts and recommends that this program be used for stormwater system design.

[2] Size limitation refers to the subwatershed size to the point where the stormwater management facility (i.e., culvert, inlet) is located.

[3] SCS is the Soil Conservation Service Method. Although the SCS is now called the Natural Resources Conservation Service, the hydrologic method is still called SCS.

[4] Will likely be less than 2000 acres in urban areas due to the need for homogeneous subwatersheds.

2.2 Symbols And Definitions

To provide consistency within this chapter, as well as throughout this manual, the following symbols will be used. These symbols were selected because of their wide use in hydrologic publications.

Table 2-2 Symbols And Definitions

Symbol	Definition	Units
A	Drainage area	acres or mi^2
C	Runoff coefficient	-
C_f	Frequency factor	-
CN	SCS-runoff curve number	-
d	Time interval	hours
F	Pond and swamp adjustment factor	-
I	Rainfall intensity	in./hr
IA	Percentage of impervious area	%
I_a	Initial abstraction from total rainfall	in.
NRCS	Natural Resources Conservation Service	-
n	Manning’s roughness coefficient	-
P	Accumulated rainfall	in.
Q	Rate of runoff	cfs
q	Storm runoff during a time interval	in.
R	Hydraulic radius	ft
S or Y	Ground slope	ft/ft or %
S	Potential maximum retention storage	in.
SCS	Soil Conservation Service	-
SL	Main channel slope	ft/ft
S_L	Standard deviation of the logarithms of the peak annual floods	-
T_B	Time base of unit hydrograph	hours
t_c or T_c	Time of concentration	min or hours
T_L	Lag time	hours
V	Velocity	ft/s

2.3 Concept Definitions

A good understanding of the following concepts will be important in any hydrologic analysis. These concepts will be used throughout the remainder of this chapter in dealing with different aspects of hydrologic studies.

Antecedent Moisture Conditions

Antecedent moisture conditions are the soil moisture conditions of the watershed at the beginning of a storm. These conditions affect the volume of runoff generated by a particular storm event. Notably they affect the peak discharge in the lower range of flood magnitudes — say below about the 15-year event threshold. As floods become more rare, antecedent moisture has a rapidly decreasing influence on runoff.

Depression Storage

Depression storage is the water stored in natural depressions within a watershed. Generally, after the depression storage is filled, runoff will commence.

Frequency

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The frequency with which a given flood can be expected to occur is the reciprocal of the probability or chance that the flood will be equaled or exceeded in a given year. If a flood has a 20 percent chance of being equaled or exceeded each year, over a long period of time, the flood will be equaled or exceeded on an average of once every five years. This is also referred to as the recurrence interval or return period.

Hydraulic Roughness

Hydraulic roughness is a measure of the physical characteristics which impede the flow of water across the earth's surface, whether natural or channelized. It affects both the time response of a watershed and drainage channel as well as the channel storage characteristics.

Hydrograph

A hydrograph is a graph of the time distribution of runoff (expressed as a flow rate) from a watershed.

Hyetographs

The hyetograph is a graph of the time distribution of rainfall (usually expressed as an intensity) over a watershed.

Infiltration

Infiltration is the complex process whereby water penetrates the ground surface and is either stored in the soil pore spaces or flows to lower layers. An infiltration curve is a graph of the time distribution at which this occurs.

Interception

Storage of rainfall on foliage and other intercepting surfaces during a rainfall event is called interception storage.

Lag Time

Lag time is defined as the time from the centroid of the excess rainfall to the peak of the hydrograph.

Peak Discharge

The peak discharge, sometimes called peak flow, is the maximum rate of flow of water passing a given point during or after a rainfall event or snowmelt.

Rainfall Excess

The rainfall excess is the water available to runoff after interception, depression storage and infiltration are satisfied.

Recurrence Interval

The time interval in which an event will occur once on the average. (i.e. a 10-year storm is expected to occur once every 10 years, on the average)

Stage

The stage of a river or other water body is the elevation of the water surface above some elevation datum.

Time Of Concentration

The time of concentration is the time it takes a drop of water falling on the hydraulically most remote point in the watershed to travel through the watershed to the outlet or design point.

Unit Hydrograph

A unit hydrograph is the storm hydrograph resulting from a rainfall event which has a specific temporal and spatial distribution, which lasts for a specific duration and has unit volume (or results from a unit depth of runoff). The ordinates of the unit hydrograph are such that the volume of runoff represented by the area under the hydrograph is equal to one inch of runoff from the drainage area. When a unit hydrograph is shown with units of cubic feet per second, it is implied that the ordinates are cubic feet per second per inch of direct runoff.

2.4 Design Frequency

2.4.1 Overview

Since it is not economically feasible to design a structure for the maximum runoff a watershed is capable of producing, a design frequency must be established. The designer should note that the 5-year flood is not one that will necessarily be equaled or exceeded every five years. There is a 20 percent chance that the flood will be equaled or exceeded in any year; therefore, the 5-year flood could conceivably occur in several consecutive years. The same reasoning applies to floods with other return periods.

2.4.2 Frequency Design Criteria

Cross Drainage: Cross drainage facilities transport storm runoff under roadways. The cross drainage facilities shall be designed to convey (at a minimum) the 50-year runoff event without overtopping the roadway. The flow rate shall be based on upstream ultimate buildout land-use conditions. In addition, the 100-year frequency storm shall be routed through all culverts to be sure structures are not flooded or increased damage does not occur to the roadway or adjacent property for this design event.

Storm drains: A storm drain shall be designed to accommodate a 5-year storm in residential areas and a 10-year storm in commercial developments, downtown areas and in industrial developments. The design shall be such that the storm runoff does not: increase the flood hazard significantly on adjacent property; encroach onto the street or highway so as to cause a safety hazard by impeding traffic, emerging vehicles, or pedestrian movements to an unreasonable extent.

Based on these criteria, a design involving temporary street or road inundation is acceptable practice for flood events greater than the design event but not for floods that are equal to or less than the design event. Thus, if a storm drainage system crosses under a roadway, the design flood must be routed through the system to show that the roadway will not be overtopped by this event. The excess storm runoff from events larger than the design storm may be allowed to inundate the roadway or may be stored in areas other than on the roadway until the drainage system can accommodate the additional runoff.

Inlets: Inlets shall be designed for a 5-year storm in residential areas and small commercial developments and a 10-year storm in downtown areas industrial developments, and arterial roads.

Detention and retention storage facilities: All storage facilities shall be designed to provide sufficient storage and release rates to accommodate the 2-, 10-, and 100-year design storm events such that the post-development peak discharges do not exceed the pre-development rates. The design shall be such that the storm runoff does not increase the flood hazard significantly for adjacent, upstream, or downstream property or cause safety hazards associated with the facility. An emergency spillway shall be provided. For storage facilities, outlet designs that provide some control for flood events below the 2-year storm (e.g., v-notch weirs) are preferred over outlets that do not provide this control (e.g., pipes). In addition, the final design shall be checked to ensure that flood peaks at the downstream property line have not increased.

2.5 Rational Method

2.5.1 Introduction

The rational method can be used to estimate the design peak discharge for areas as large as 150 acres. This method, while first introduced in 1889, is still used in many engineering offices in the United States. Even though it has frequently come under criticism for its simplistic approach, no other drainage design method has received such widespread use.

2.5.2 Concept and Equation

The rational formula estimates the peak rate of runoff at any location in a watershed as a function of the drainage area, runoff coefficient, and mean rainfall intensity for a duration equal to the time of concentration (the time required for water to flow from the hydraulically most remote point of the basin to the location being analyzed). The rational formula is expressed as follows:

$$Q = CIA \tag{2.1}$$

where: Q = peak rate of runoff, cfs
C = runoff coefficient representing a ratio of runoff to rainfall for future land-use conditions
I = average rainfall intensity for a duration equal to the time of concentration, for a selected return period in./hr (see Figure 2-3)
A = drainage area tributary to the design location, acres

2.5.3 Application

Peak discharges estimated using the rational formula are very sensitive to the parameters that are used. The designer must use good engineering judgment in assigning values to these parameters. Each of the parameters used in the rational method is discussed below.

2.5.3.1 Time Of Concentration

The time of concentration (t_c) is the time required for water to flow from the hydraulically most remote point of the drainage area to the point under investigation. Use of the rational formula requires the time of concentration (t_c) for each design point within the drainage basin. The duration of rainfall is then set equal to the time of concentration and is used to estimate the rainfall intensity (I). For a storm drain system, the time of concentration consists of an inlet time plus the time of flow in a closed conduit or open channel to the design point. Inlet time is the time required for runoff to flow over the surface to the nearest inlet and is primarily a function of the length of overland flow, the slope of the land and surface cover. Pipe or open channel flow time can be estimated from the hydraulic properties of the conduit or channel. One way to estimate overland flow time is to use Figure 2-1 to estimate overland flow velocity and divide the velocity into the overland travel distance.

For design situations that do not involve complex drainage conditions, Figure 2-2 can be used to estimate inlet time. For each drainage area, the distance is determined from the inlet to the most remote point in the tributary area. From a topographic map, the average slope is determined for the same distance. The Coefficient of Runoff, C is determined by the procedure described in a subsequent section of this chapter.

To obtain the total time of concentration, the pipe or open channel flow time must be calculated and added to the inlet time. After first determining the average flow velocity in the pipe or channel, the travel time is obtained by dividing velocity into the pipe or channel length. Manning's equation can be used to determine velocity. See Chapter 5 - Open Channel Hydraulics - for a discussion of Manning's equation.

Time of concentration is an important variable in most hydrologic methods. Several methods are available for estimating t_c. Appendix 2-C (Travel Time Estimation) at the end of this chapter describes the method from the SCS Technical Release No. 55 (2nd Edition). Figure 2-2 shows the velocities used for estimating time of concentration for various land use conditions. For inlet design the minimum t_c recommended should not be less than 8 minutes.

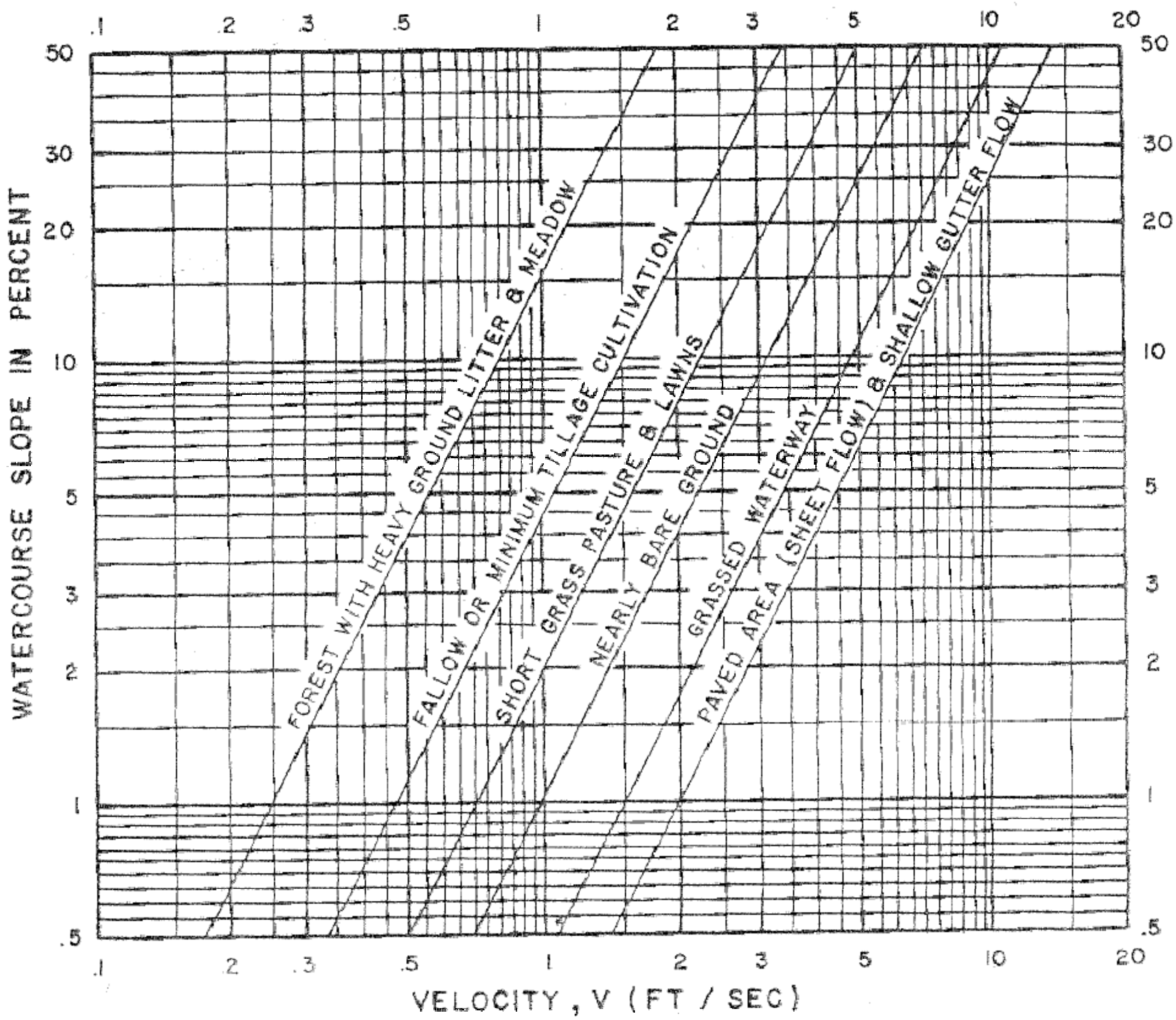

Figure 2-1 Velocities For Estimating Time Of Concentration

Source: HEC No. 19, FHWA

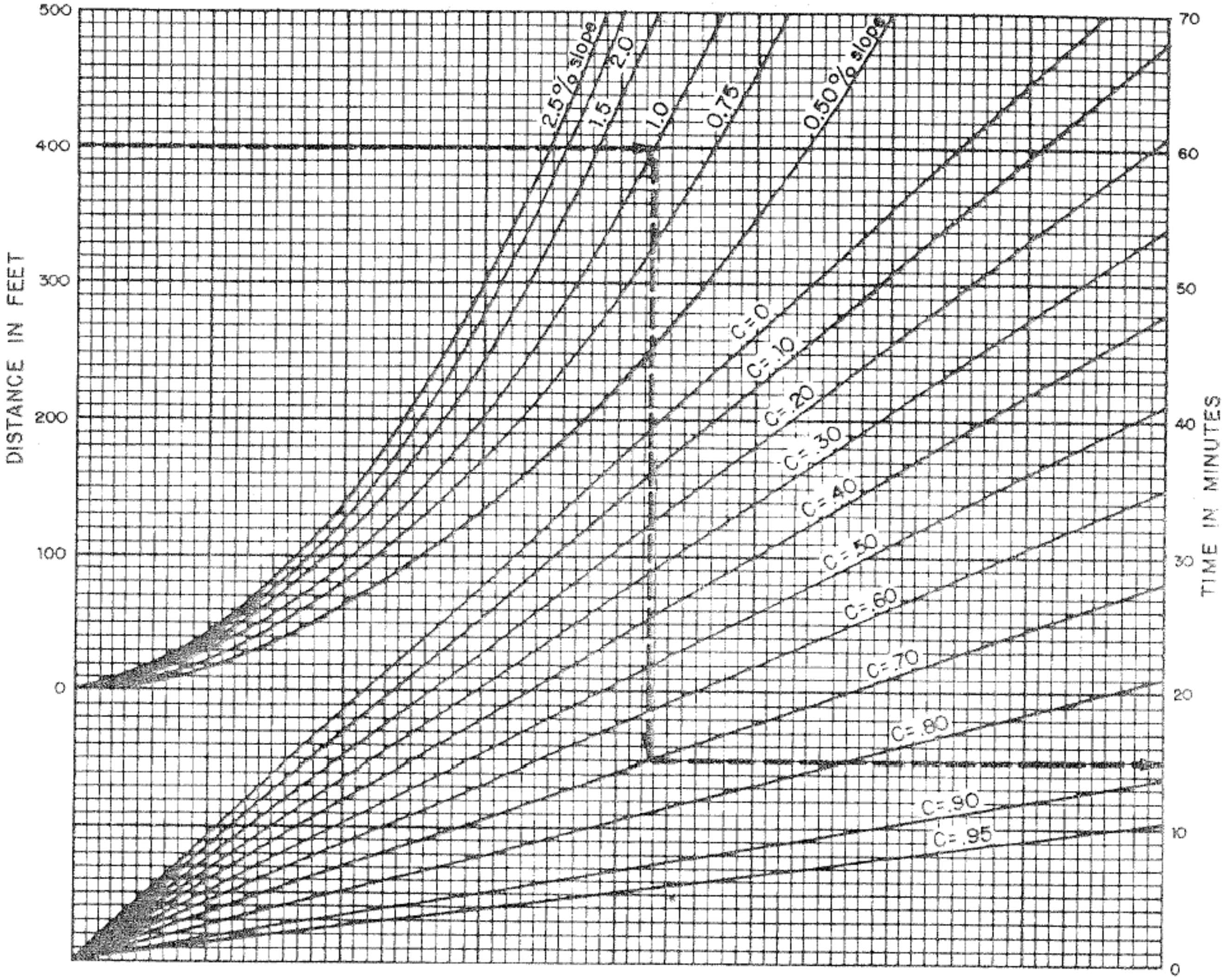

Figure 2-2 Overland Time Of Flow

Source: Airport Drainage, Federal Aviation Administration, 1965

2.5.3.1.1 Common Errors

Two common errors should be avoided when calculating t_c. First, in some cases runoff from a portion of the drainage area which is highly impervious may result in a greater peak discharge than would occur if the entire area were considered. In these cases, adjustments can be made to the drainage area by disregarding those areas where flow time is too slow to add to the peak discharge. Sometimes it is necessary to estimate several different times of concentration to determine the design flow that is critical for a particular application.

Second, when designing a drainage system, the overland flow path is not necessarily perpendicular to the contours shown on available mapping. Often the land will be graded and swales will intercept the natural contour and conduct the water to the streets, which reduces the time of concentration. Care should be exercised in selecting sheet flow paths in excess of 100 ft in urban areas and 300 ft in rural areas. Sheet flow conditions are not likely to be sustained for greater lengths and the estimated T_c will be too large.

2.5.3.2 Rainfall Intensity

The rainfall intensity (I) is the average rainfall rate (in./hr) for a duration equal to the time of concentration for a selected return period. Once a particular return period has been selected for design and a time of concentration calculated for the drainage area, the rainfall intensity can be determined from Intensity-Duration-Frequency (IDF) curves. The data from the IDF curve for the City of Lincoln are given in Figure 2-3.

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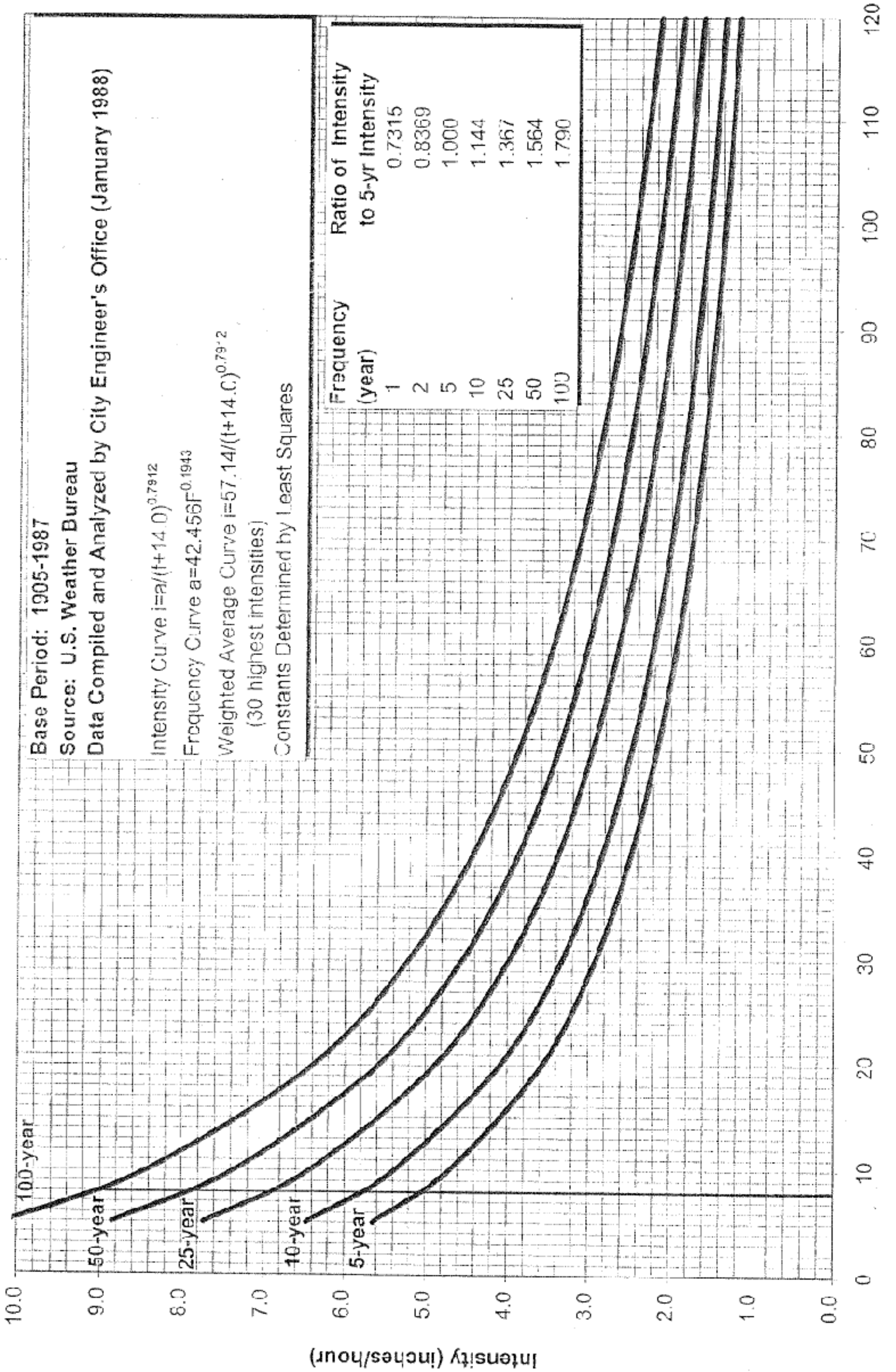

Figure 2-3 Intensity-Duration-Frequency Curves
Lincoln, Nebraska

Source: Lincoln Public Works and Utilities Department

2.5.3.3 Runoff Coefficient

The runoff coefficient (C) is the variable of the rational method least susceptible to precise determination and requires judgment and understanding on the part of the designer. Engineering judgment will always be required in the selection of runoff coefficients since a typical coefficient represents the integrated effects of many drainage basin parameters. The following discussion considers only the effects of soil groups, land use and average land slope.

The method for determining the runoff coefficient (C) is based on land use, soil groups and land slope. Table 2-4 in Manual gives the recommended coefficient C of runoff for pervious surfaces by selected hydrologic soil groupings and slope ranges. *The value of C shall be based on fully built-out land use conditions. The minimum runoff coefficient shall be 0.4 , unless owner can clearly demonstrate that the value less then 0.4 is adequate.*

Table 2-4 gives the recommended coefficient C of runoff for pervious surfaces by selected hydrologic soil groupings and slope ranges. From this table the C values for non-urban areas such as forest land, agricultural land, and open space can be determined. Soil properties influence the relationship between runoff and rainfall since soils have differing rates of infiltration. Infiltration is the movement of water through the soil surface into the soil. Based on infiltration rates, the Soil Conservation Service (SCS) has divided soils into four hydrologic soil groups as follows:

Group A Soils having a low runoff potential due to high infiltration rates. These soils consist primarily of deep, well-drained sands and gravels.

Group B Soils having a moderately low runoff potential due to moderate infiltration rates. These soils consist primarily of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures.

Group C Soils having a moderately high runoff potential due to slow infiltration rates. These soils consist primarily of soils in which a layer exists near the surface that impedes the downward movement of water or soils with moderately fine to fine texture.

Group D Soils having a high runoff potential due to very slow infiltration rates. These soils consist primarily of clays with high swelling potential, soils with permanently high water tables, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious parent material.

A list of soils for the City of Lincoln and their hydrologic classification is presented in the Lancaster County Soil Survey.

As the slope of the drainage basin increases, the selected C value should also increase. This is caused by the fact that as the slope of the drainage area increases, the velocity of overland and channel flow will increase, allowing less opportunity for water to infiltrate. Thus, more of the rainfall will become runoff from the drainage area.

It is often desirable to develop a composite runoff coefficient based on the percentage of different types of surface in the drainage area. Composites can be made with Tables 2-3 and 2-4. The composite procedure can be applied to an entire drainage area or to typical "sample" blocks as a guide to selection of reasonable values of the coefficient for an entire area.

Table 2-3 Recommended Coefficient Of Runoff Values For Various Selected Land Uses

Description of Area	Runoff Coefficients
Business: Downtown areas	0.70-0.95
Neighborhood areas	0.50-0.70
Residential: Single-family areas	0.30-0.50
Multi units, detached	0.40-0.60
Multi units, attached	0.60-0.75
Suburban	0.25-0.40
Residential (1 acre lots or larger)	0.30-0.45
Apartment dwelling areas	0.50-0.70
Industrial: Light areas	0.50-0.80
Heavy areas	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.40
Railroad yard areas	0.20-0.40
Unimproved areas	0.04-0.38 (see Table 2-4)

Source: Hydrology, Federal Highway Administration, HEC No. 19, 1984

Table 2-4 Recommended Coefficient Of Runoff For Pervious Surfaces (Unimproved Areas) By Selected Hydrologic Soil Groupings And Slope Ranges

Slope	A	B	C	D
Flat (0 - 1%)	0.04-0.09	0.07-0.12	0.11-0.16	0.15-0.20
Average (2 - 6%)	0.09-0.14	0.12-0.17	0.16-0.21	0.20-0.25
Steep (Over 6%)	0.13-0.18	0.18-0.24	0.23-0.31	0.28-0.38

Source: Storm Drainage Design Manual, Erie and Niagara Counties Regional Planning Board.

2.5.3.3.1 Infrequent Storm

The coefficients given in Tables 2-3 and 2-4 are applicable for storms of 5-year to 10-year frequencies. Less frequent, higher intensity storms will require modification of the coefficient because infiltration and other losses have a proportionally smaller effect on runoff (Wright-McLaughlin, 1969). The adjustment of the rational method for use with major storms can be made by multiplying the right side of the rational formula by a frequency factor C_f. The rational formula now becomes:

$$\mathbf{Q = C_f CIA} \qquad \textbf{(2.1)}$$

C_f values are listed in Table 2-5. The product of C_f times C shall not exceed 1.0.

Table 2-5 Frequency Factors For Rational Formula

Recurrence Interval (years)	C_f
25	1.1
50	1.2
100	1.25

2.5.4 Limitations

Some precautions should be considered when applying the rational method.

- The first step in applying the rational method is to obtain a good topographic map and define the boundaries of the drainage area in question. A field inspection of the area should also be made to determine if the natural drainage divides have been altered.
- In determining the runoff coefficient (C) value for the drainage area, thought should be given to future changes in land use that might occur during the service life of the proposed facility that could result in an inadequate drainage system. Also, the effects of permanent upstream detention facilities may be taken into account.
- Restrictions to the natural flow such as highway crossings and dams that exist in the drainage area should be investigated to see how they affect the design flows.
- The charts, graphs and tables included in this section are not intended to replace reasonable and prudent engineering judgment which should permeate each step in the design process.

Characteristics of the rational method which limit its use to 150 acres include:

(1) The rate of runoff resulting from any rainfall intensity is a maximum when the rainfall intensity lasts as long or longer than the time of concentration. That is, the entire drainage area does not contribute to the peak discharge until the time of concentration has elapsed.

This assumption limits the size of the drainage basin that can be evaluated by the rational method. For large drainage areas, the time of concentration can be so large that constant rainfall intensities for such long periods do not occur and shorter, more intense rainfalls can produce larger peak flows.

(2) The frequency of peak discharges is the same as that of the rainfall intensity for the given time of concentration.

Frequencies of peak discharges depend on rainfall frequencies, antecedent moisture conditions in the watershed, and the response characteristics of the drainage system. For small and largely impervious areas, rainfall frequency is the dominant factor. For larger drainage basins and undeveloped drainage basins, the response characteristics control the frequencies of peak discharges. For drainage areas with few impervious surfaces (less urban development), antecedent moisture conditions usually govern, especially for rainfall events with a return period of 10 years or less.

(3) The fraction of rainfall that becomes runoff (C) is independent of rainfall intensity or volume.

This assumption is reasonable for impervious areas, such as streets, rooftops and parking lots. For pervious areas, the fraction of runoff varies with rainfall intensity and the accumulated volume of rainfall. Thus, the “art” necessary for application of the rational method involves the selection of a coefficient that is appropriate for the storm, soil and land use conditions. Many guidelines and tables have been established, but seldom, if ever, have they been supported with empirical evidence.

(4) The rational method provides estimates of only peak discharge rates of runoff. It does not provide information on the volume of runoff.

Modern drainage practice often includes detention of urban storm runoff to reduce the peak rate of runoff downstream. With only the peak rate of runoff, the rational method severely limits the evaluation of design alternatives available in urban and in some instances, rural drainage design.

Thus, the rational formula is best suited for small, highly impervious areas and least suitable for large drainage areas or drainage areas in natural or undeveloped conditions.

2.5.5 Example Problem - Rational Method

The following example problem illustrates the application of the rational method to estimate peak discharges. Preliminary estimates of the maximum rate of runoff are needed at the inlet to a culvert for a 10-year and 100-year return period.

Site Data

From a topographic map and field survey, the area of the drainage basin upstream from the culvert found to be 18 acres. In addition the following data were measured:

Length of overland flow = 50 ft
Average overland slope = 2.0%
Length of main basin channel = 1300 ft
Slope of channel = 0.018 ft/ft = 1.8%
Hydraulic radius = 1.97 ft
Estimated roughness coefficient (n) of channel = 0.090

Land Use And Soil Data

From existing land use maps, land use for the drainage basin was estimated to be:

Residential (single family)	80%
Undeveloped (2% slope)	20%

For the undeveloped area, the soil group was determined from a SCS map to be:

Group B	100%

From existing land use maps, the land use for the overland flow area at the head of the basin was estimated to be:

Undeveloped (Soil Group B, 2.0% slope)	100%

Overland Flow

A runoff coefficient (C) for the overland flow area was determined to be 0.12 from Table 2-4.

Time Of Concentration

From Figure 2-2, with an overland flow length of 50 ft, slope of 2.0%, and a C of 0.12, the inlet time is 10 min. Channel flow velocity is determined from Manning's formula to be 3.5 ft/s (n = 0.090, R = 1.97 ft and S = 0.018 ft/ft). Therefore,

Flow Time = (1300 ft)/(3.5 ft/s)(60 s/min) = 6.2 min
and t_c = 10 + 6.2 = 16.2 min - say 16 min

Rainfall Intensity

From Figure 2-3 with duration equal to 16 min,

I_{10} (10-year return period) = 4.50 in./hr

I_{100} (100-year return period) = 7.05 in./hr

Runoff Coefficient

A weighted runoff coefficient C for the total drainage area is determined in Table 2-6 by utilizing the values from Tables 2-3 and 2-5.

Table 2-6 Weighted Runoff Coefficient, C

Land Use	(1) Percent of Total Land Area	(2) Weighted Runoff Coefficient	(3) Runoff Coefficient*
Residential (single family)	0.80	0.40	0.32
Undeveloped (Soil Group B)	0.20	0.12	0.02
Total Weighted Runoff Coefficient			0.34

* Column 3 equals column 1 multiplied by column 2.

Peak Runoff

From the rational equation:

Q_{10} = CIA = 0.34 × 4.50 × 18 = 28 cfs

Q_{100} = C_fCIA = 1.25 × 0.34 × 7.05 × 18 = 54 cfs From Table 2.5

These are the estimates of peak runoff for a 10-year and 100-year design storm for the given basin.

2.6 SCS Unit Hydrograph Method

2.6.1 Introduction

Techniques developed by the U. S. Soil Conservation Service for calculating rates of runoff require the same basic data as the rational method: drainage area, a runoff factor, time of concentration and rainfall. The SCS approach, however, is more sophisticated in that it considers also the time distribution of the rainfall, the initial rainfall losses to interception and depression, storage and an infiltration rate that decreases during the course of a storm. With the SCS method, the direct runoff can be calculated for any storm, either real or fabricated, by subtracting infiltration and other losses from the rainfall to obtain the precipitation excess (runoff volume). Details of the methodology can be found in the SCS National Engineering Handbook, Section 4.

Two types of hydrographs are used in the SCS procedure, unit hydrographs and dimensionless hydrographs. A unit hydrograph represents the time distribution of flow resulting from one inch of direct runoff occurring over the watershed in a specified time. A dimensionless hydrograph represents the composite of many unit hydrographs. The dimensionless unit hydrograph is plotted in nondimensional units of time divided by time to peak and discharge divided by peak discharge.

Characteristics of the dimensionless hydrograph vary with the size, shape and slope of the tributary drainage area. The most significant characteristics affecting the dimensionless hydrograph shape are the basin lag and the peak discharge for a given rainfall. Basin lag is the time from the center of mass of rainfall excess to the hydrograph peak. Steep slopes, compact shape and an efficient drainage network tend to make lag time short and peaks high; flat slopes, elongated shape and an inefficient drainage network tend to make lag time long and peaks low.

2.6.2 Concepts and Equations

The following discussion outlines the basic concepts and equations utilized in the SCS method.

2.6.2.1 Rainfall-Runoff

Rainfall-Runoff Equation - A relationship between accumulated rainfall and accumulated runoff was derived by SCS from experimental plots for numerous soils and vegetative cover conditions. Data for land-treatment measures, such as contouring and terracing, from experimental watersheds were included. The equation was developed mainly for small watersheds from which only daily rainfall and watershed data are ordinarily available. It was developed from recorded storm data that included the total amount of rainfall in a calendar day but not its distribution with respect to time. The SCS runoff equation is therefore a method of estimating direct runoff from 24-hr or 1-day storm rainfall. The equation is:

$$\mathbf{Q = (P - I_a)^2 \ / \ (P - I_a) + S} \qquad \textbf{(2.2)}$$

Where:
- Q = accumulated direct runoff, in.
- P = accumulated rainfall (potential maximum runoff), in.
- I_a = initial abstraction including surface storage, interception and infiltration prior to runoff, in.
- S = potential maximum retention, in.

The relationship between I_a and S was developed from experimental watershed data. It eliminates the need for estimating I_a for common usage. The empirical relationship used in the SCS runoff equation is:

$$I_a = 0.2S \tag{2.3}$$

By substituting 0.2S for I_a in equation 2.3, the SCS rainfall-runoff equation becomes:

$$Q = (P - 0.2S)^2 / (P + 0.8S) \tag{2.4}$$

S is related to the soil and cover conditions of the watershed through the curve number (CN) or runoff factor (See Section 2.6.3.1). CN has a range of 0 to 100, and S is related to CN by:

$$S = (1000 / CN) - 10 \tag{2.5}$$

Figure 2-4 is a graphical solution of equation 2.4 which enables the precipitation excess (runoff depth) from a storm to be obtained if the total rainfall and watershed curve number are known.

Drainage Area - The drainage area of a watershed is determined from topographic maps and field surveys. For large drainage areas it might be necessary to divide the area into sub-drainage areas to account for major land use changes, to obtain analysis results at different points within the drainage area, or to locate stormwater drainage facilities and assess their effects on the flood flows. Also a field inspection of existing or proposed drainage systems should be made to determine if the natural drainage divides have been altered. These alterations could make significant changes in the size and slope of the subdrainage areas.

Rainfall - The SCS method is based on a 24-hr storm event with various time distributions, depending on the watershed location. The Type II storm distribution is a "typical" time distribution which the SCS has prepared from rainfall records and can be used in Lincoln, Nebraska. Figure 2-5 shows this distribution. To use this distribution it is necessary for the user to obtain the 24-hr duration rainfall value for the frequency of the design storm desired from the Table 2-7.

Table 2-7 City Of Lincoln 24-Hour Design Rainfall

Frequency	24-hour Rainfall	Frequency	24-hour Rainfall
2-year	3.00 in.	25-year	5.37 in.
5-year	3.93 in.	50-year	6.00 in.
10-year	4.69 in.	100-year	6.68 in.

Source: National Weather Service, Tech. Paper 40, “Rainfall Frequency Atlas of the U.S.”, May 1961.

2.6.2.2 Time Of Concentration

The average slope within the watershed together with the overall length and retardance of overland flow are the major factors affecting the runoff rate through the watershed. In the SCS method, time of concentration (t_c) is defined to be the time required for water to travel from the most hydraulically distant point in a watershed to its outlet. Lag (L) can be considered as a weighted time of concentration and is related to the physical properties of a watershed, such as area, length and slope. The SCS derived the following empirical relationship between lag and time of concentration:

$$L = 0.6\, t_c \tag{2.6}$$

See Appendix 2-C for information on the derivation of t_c.

In small urban areas (less than 2000 acres), a curve number method can be used to estimate the time of concentration from watershed lag. In this method the lag for the runoff from an increment of excess rainfall can be considered as the time between the center of mass of the excess rainfall increment and the peak of its incremental outflow hydrograph. The equation developed by SCS to estimate lag is:

$$\mathbf{L = (l^{0.8}\ (S + 1)^{0.7}) / (1900\ Y^{0.5})} \qquad \mathbf{(2.7)}$$

Where: L = lag, hrs
l = length of mainstream to farthest divide, ft
Y = average slope of watershed, %
S = (1000/CN) - 10
CN = SCS curve number

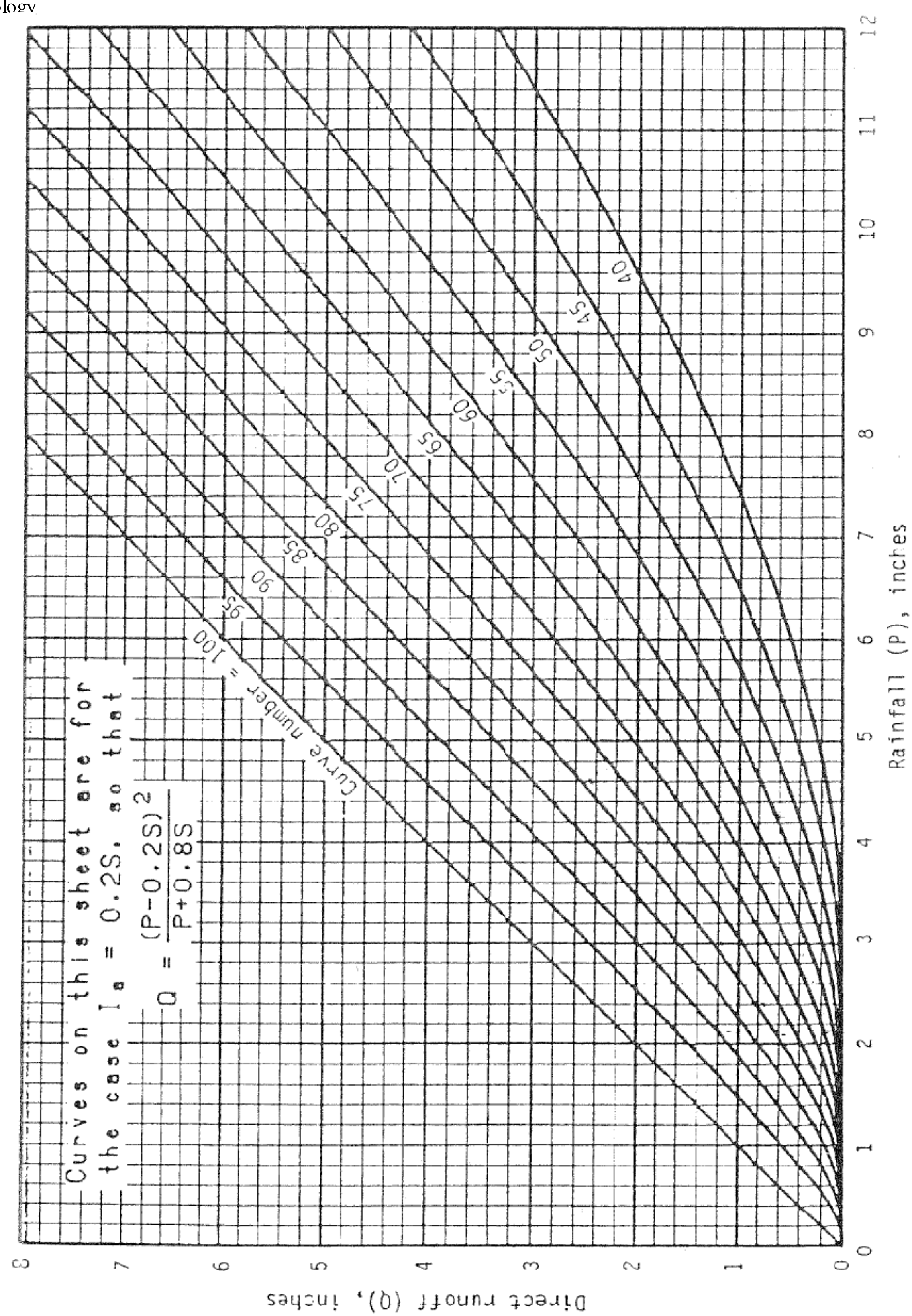

Figure 2-4 SCS Relation Between Direct Runoff, Curve Number And Precipitation

Source: HEC 19

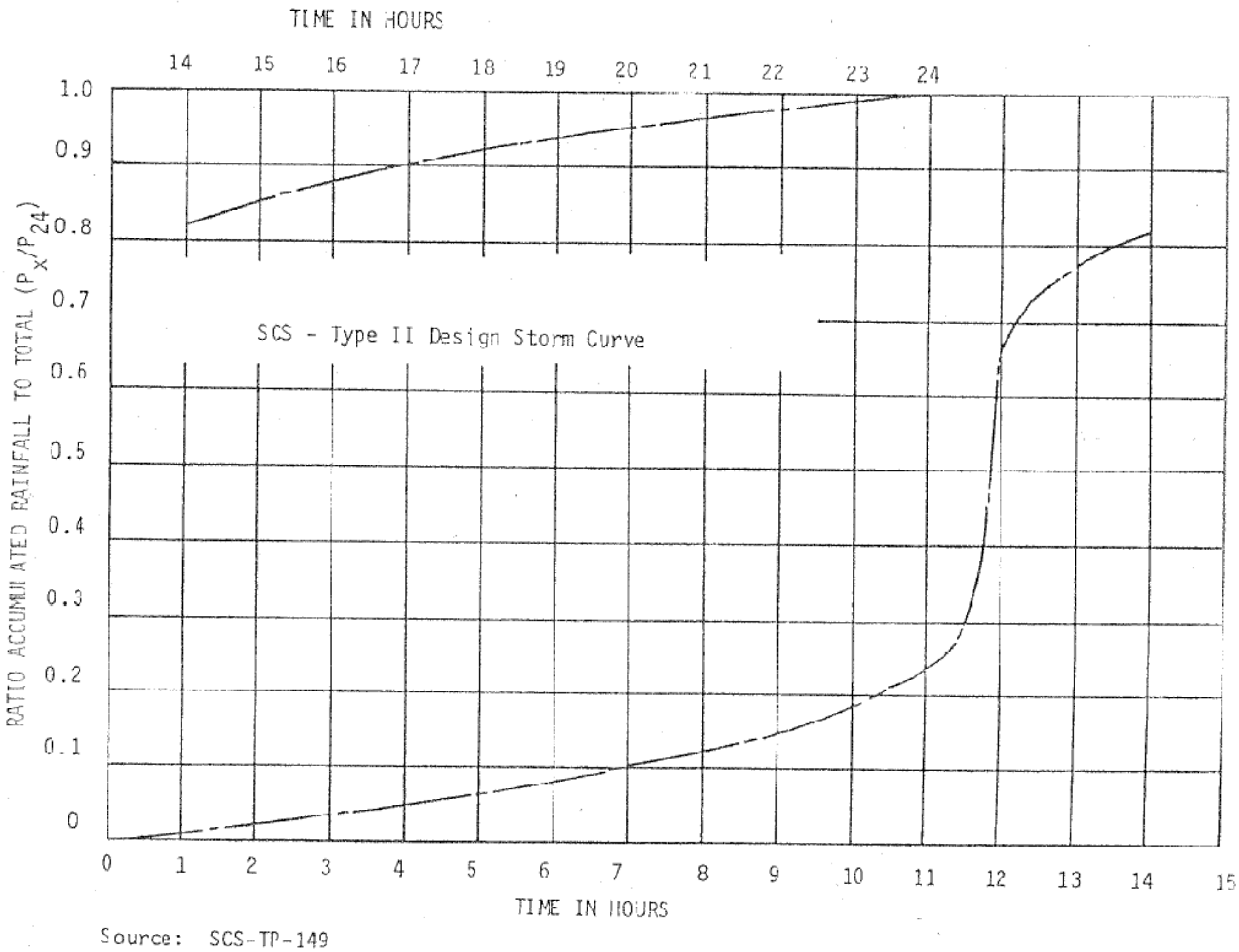

Figure 2-5 Type II Design Storm Curve

The lag time can be corrected for the effects of urbanization by using Figures 2-6 and 2-7. The amount of modifications to the hydraulic flow length usually must be determined from topographic maps or aerial photographs following a field inspection of the area. The modification to the hydraulic flow length not only includes pipes and channels but also the length of flow in streets and driveways.

After the lag time is adjusted for the effects of urbanization, the above equation that relates lag time and time of concentration can be used to calculate the time of concentration for use in the SCS method. Appendix 2-c presents an alternate procedure for travel time and time of concentration estimation.

2.6.2.3 Triangular Hydrograph Equation

The triangular hydrograph is a practical representation of excess runoff with only one rise, one peak and one recession. Its geometric makeup can be easily described mathematically, which makes it very useful in the processes of estimating discharge rates. The SCS developed the following equation to estimate the peak rate of discharge for an increment of runoff:

$$q_p = (484\ A\ (q / (d/2 + L))) \qquad \textbf{(2.8)}$$

Where: q_p = peak rate of discharge, cfs
A = area, mi^2
q = storm runoff during time interval, in.
d = time interval, hrs
L = watershed lag, hrs

This equation can be used to estimate the peak discharge for the unit hydrograph which can then be used to estimate the peak discharge and hydrograph from the entire watershed.

The constant 484, or peak rate factor, is valid for the SCS dimensionless unit hydrograph. Any change in the dimensionless unit hydrograph reflecting a change in the percent of volume under the rising side would cause a corresponding change in the shape factor associated with the triangular hydrograph and therefore a change in the constant 484. This constant has been known to vary from about 600 in steep terrain to 300 in very flat, swampy country.

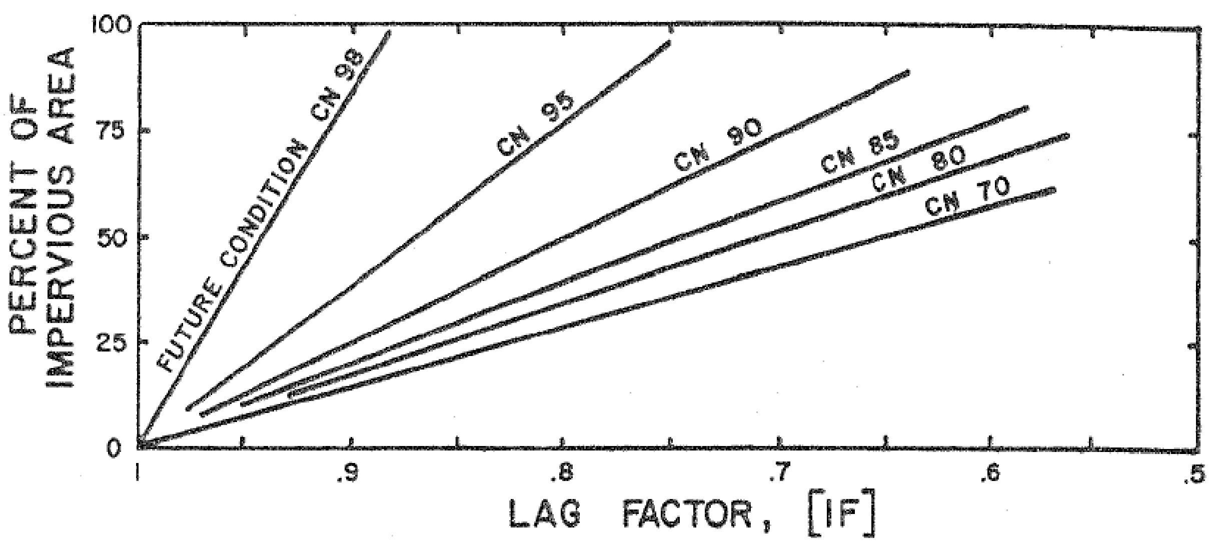

Figure 2-6 Factors For Adjusting Lag When Impervious Areas Occur In Watershed

Source: HEC-19

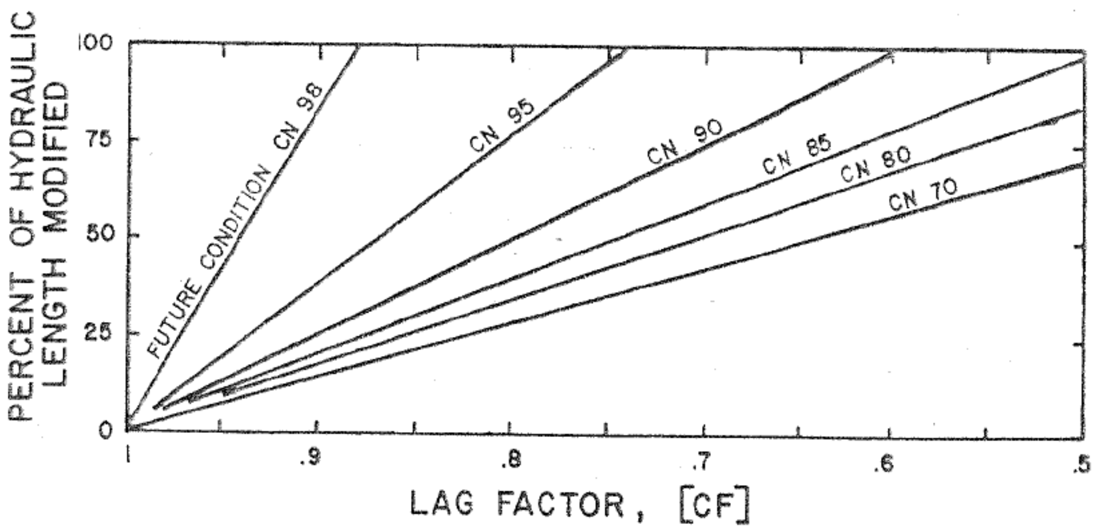

Figure 2-7 Factors For Adjusting Lag When The Main Channel Has Been Hydraulically Improved

Source: HEC 19

2.6.3 Application

The following discussion describes the procedures used in the SCS unit hydrograph method along with recommended design aids.

2.6.3.1 Runoff Factor

In hydrograph applications, runoff is often referred to as rainfall excess or effective rainfall — all defined as the amount by which rainfall exceeds the capability of the land to infiltrate or otherwise retain the rainfall. The principal physical watershed characteristics affecting the relationship between rainfall and runoff are land use, land treatment, soil types and land slope.

Land use is the watershed cover, and it includes both agricultural and nonagricultural uses. Items such as type of vegetation, water surfaces, roads, roofs, etc. are all part of the land use. Land treatment applies mainly to agricultural land use, and it includes mechanical practices such as contouring or terracing and management practices such as rotation of crops.

The SCS uses a combination of soil conditions and land-use (ground cover) to assign a runoff factor to an area. These runoff factors, called runoff curve numbers (CN), indicate the runoff potential of an area when the soil is not frozen. The higher the CN, the higher is the runoff potential.

Soil properties influence the relationship between rainfall and runoff by affecting the rate of infiltration. The SCS has divided soils into four hydrologic soil groups based on infiltration rates (Groups A, B, C and D). These groups were previously described for the rational method. Refer to Lancaster County Soil Survey.

Consideration should be given to the effects of urbanization on the natural hydrologic soil group. If heavy equipment can be expected to compact the soil during construction or if grading will mix the surface and subsurface soils, appropriate changes should be made in the soil group selected. Also, runoff curve numbers vary with the antecedent soil moisture conditions, defined as the amount of rainfall occurring in a selected period preceding a given storm. In general, the greater the antecedent rainfall, the more direct runoff there is from a given storm. A 5-day period is used as the minimum for estimating antecedent moisture conditions.

The following pages give a series of tables related to runoff factors. The first tables (Tables 2-8 - 2-10) give curve numbers for various land uses. These tables are based on an average antecedent moisture condition, i.e., soils that are neither very wet nor very dry when the design storm begins. Curve numbers should be selected only after a field inspection of the watershed and a review of zoning and soil maps. Table 2-11 gives conversion factors to convert average curve numbers to wet and dry curve numbers. Table 2-12 gives the antecedent conditions for the three classifications.

Table 2-8 Runoff Curve Numbers - Urban Areas[1]

Cover type and hydrologic condition	Average percent impervious area[2]		Curve numbers for hydrologic soil groups A	B	C	D
Fully developed urban areas (vegetation established)						
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]						
Poor condition (grass cover <50%)			68	79	86	89
Fair condition (grass cover 50% to 75%)			49	69	79	84
Good condition (grass cover > 75%)			39	61	74	80
Impervious areas:						
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)			98	98	98	98
Streets and roads:						
Paved; curbs and storm drains (excluding right-of-way)			98	98	98	98
Paved; open ditches (including right-of-way)			83	89	92	93
Gravel (including right-of-way)			76	85	89	91
Dirt (including right-of-way)			72	82	87	89
Urban districts:						
Commercial and business	85%		89	92	94	95
Industrial	72%	81	88	91	93	
Residential districts by average lot size:						
1/8 acre or less (town houses)	65%	77	85	90	92	
1/4 acre	38%		61	75	83	87
1/3 acre	30%		57	72	81	86
½ acre	25%		54	70	80	85
1 acre	20%		51	68	79	84
2 acres	12%		46	65	77	82
Developing urban areas						
Newly graded areas (pervious areas only, no vegetation)			77	86	91	94
Idle lands (CNs are determined using cover types similar to those in Table 2-10).						

[1] Average runoff condition, and $I_a = 0.2S$

[2] The average percent impervious area shown was used to develop the composite CNs. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. If the impervious area is not connected, the SCS method has an adjustment to reduce the effect.

[3] CNs shown are equivalent to those of pasture. Composite CNs may be computed for other combinations of open space cover type.

Source: TR-55

Table 2-9 Cultivated Agricultural Land[1]

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment[2]	Hydrologic condition[3]	A	B	C	D
Fallow	Bare soil	-	77	86	91	94
	Crop residue	Poor	76	85	90	93
	cover (CR)	Good	74	83	88	90
Row Crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured &	Poor	66	74	80	82
	terraced (C&T)	Good	62	71	78	81
	C&T + CR	Poor	65	73	79	81
		Good	61	70	77	80
	Small grain SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + CR	Poor	60	71	78	81
		Good	58	69	77	80
	Close-seeded SR	Poor	66	77	85	89
	or broadcast	Good	58	72	81	85
	Legumes or C	Poor	64	75	83	85
	Rotation	Good	55	69	78	83
	Meadow C&T	Poor	63	73	80	83
		Good	51	67	76	80

[1] Average runoff condition, and $I_a = 0.2S$.

[2] Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

[3]Hydrologic condition is based on a combination of factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or closed-seeded legumes in rotations, (d) percent of residue cover on the land surface (good > 20%) and (e) degree of roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Source: TR-55

Table 2-10 Other Agricultural Lands[1]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range-continuous forage for grazing[2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, —protected from grazing and generally mowed for hay		30	58	71	78
Brush—brush-weed-grass mixture with brush the major element[3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	[4]30	48	65	73
Woods—grass combination (orchard or tree farm)[5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods[6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	[4]30	55	70	77
Farmsteads—buildings, lanes, driveways and surrounding lots	—	59	74	82	86

[1] Average runoff condition, and $I_a = 0.2S$

[2] Poor: < 50% ground cover or heavily grazed with no mulch
Fair: 50 to 75% ground cover and not heavily grazed
Good: > 75% ground cover and lightly or only occasionally grazed

[3] Poor: < 50% ground cover
Fair: 50 to 75% ground cover
Good: > 75% ground cover

[4] Actual curve number is less than 30; use CN = 30 for runoff computations.

[5] CNs shown were computed for areas with 50% grass (pasture) cover. Other combinations of conditions may be computed from CNs for woods and pasture.

[6] Poor: Forest litter, small trees and brush are destroyed by heavy grazing or regular burning.
Fair: Woods grazed but not burned, and some forest litter covers the soil.
Good: Woods protected from grazing, litter and brush adequately cover soil.

Source: TR-55

Table 2-11 Conversion From Average Antecedent Moisture Conditions To Dry And Wet Conditions

CN For Average Conditions	Corresponding CNs For Dry	Corresponding CNs For Wet
100	100	100
95	87	98
90	78	96
85	70	94
80	63	91
75	57	88
70	51	85
65	45	82
60	40	78
55	35	74
50	31	70
45	26	65
40	22	60
35	18	55
30	15	50
25	12	43
15	6	30
5	2	13

Source: USDA Soil Conservation Service TP-149 (SCS-TP-149), "A Method for Estimating Volume and Rate of Runoff in Small Watersheds," revised April 1973.

Table 2-12 Rainfall Groups For Antecedent Soil Moisture Conditions During Growing And Dormant Seasons

Antecedent Condition	Conditions Description	Growing Season 5-day Antecedent Rainfall	Dormant Season 5-day Antecedent Rainfall
Dry	An optimum condition of watershed soils, where soils are dry but not to the wilting point and when satisfactory plowing or cultivation takes place	Less than 1.4 in.	Less than 0.5 in.
Average	The average case for annual floods	1.4 - 2.1 in.	0.5 - 1.1 in.
Wet	When a heavy rainfall, or light rainfall and low temperatures, have occurred during the five days previous to a given storm	Over 2.1 in.	Over 1.1 in.

Source: Soil Conservation Service

2.6.4 Limitations

Several factors, such as the percentage of impervious area and the means of conveying runoff from impervious areas to the drainage system, should be considered in computing CN for urban areas. For example, do the impervious areas connect directly to the drainage system, or do they outlet onto lawns or other pervious areas where infiltration can occur?

The curve number values given in Table 2-8 are based on directly connected impervious area. An impervious area is considered directly connected if runoff from it flows directly into the drainage system. It is also considered directly connected if runoff from it occurs as concentrated shallow flow that runs over a pervious area and then into a drainage system. It is possible that curve number values from urban areas could be reduced by not directly connecting impervious surfaces to the drainage system. For a discussion of impervious areas and their effect on curve number values, see Appendix 2-B at the end of this chapter.

2.7 Simplified SCS Method

2.7.1 Introduction

The following SCS procedures were taken from the SCS Technical Release 55 (TR-55) which presents simplified procedures to calculate storm runoff volume, peak rate of discharges and hydrographs. These procedures allow manual calculation of hydrologic parameters. HEC-HMS performs the same calculations when the SCS methodology is selected within the software package. These procedures are applicable to small drainage areas and include provisions to account for urbanization. The following procedures outline the use of the SCS-TR 55 method.

2.7.2 Concepts and Equations - Peak Discharge Method

The SCS peak discharge method is applicable for estimating the peak run-off rate from watersheds with homogeneous land uses. The following method is based on the results of computer analyses performed using TR-20, "Computer Program for Project Formulation - Hydrology" (SCS 1983).

The peak discharge equation is:

$$\mathbf{Q_p = q_u A Q F_p} \qquad \textbf{(2.9)}$$

Where:

Q_p = peak discharge (cfs)
q_u = unit peak discharge (cfs/mi^2/in.)
A = drainage area (mi^2)
Q = runoff (in.)
F_p = pond and swamp adjustment factor

The input requirements for this method are as follows:

1. Time of concentration, T_c (hours)
2. Drainage area (mi^2)
3. Type II rainfall distribution
4. 24-hour design rainfall
5. CN value
6. Pond and swamp adjustment factor (If pond and swamp areas are spread throughout the watershed and are not considered in the T_c computation, an adjustment is needed.)

Computations for the peak discharge method proceed as follows:

1. The 24-hour rainfall depth is determined from Table 2-7.

2. The runoff curve number, CN, is estimated from Table 2-8 through 2-10 and direct runoff, Q, is calculated using equation 2.4.

3. The CN value is used to determine the initial abstraction, I_a, from Table 2-13, and the ratio I_a/P is then computed. (P = accumulated rainfall or potential maximum runoff.)

4. The watershed time of concentration is computed using the procedures in Section 2.6.2.2 and is used with the ratio I_a/P to obtain the unit peak discharge, q_u, from Figure 2-8 or the method given in Appendix 2-C. If the ratio I_a/P lies outside the range shown in Figure 2-8, either the limiting values or another peak discharge method should be used.

5. The pond and swamp adjustment factor, F_p, is estimated from the following information:

Pond & Swamp Areas (%)	F_p	Pond & Swamp Areas (%)	F_p
0	1.00	3.0	0.75
0.2	0.97	5.0	0.72
1.0	0.87		

6. The peak runoff rate is computed using equation 2.9.

Table 2-13 I_a Values For Runoff Curve Numbers

Curve Number	I_a (in)	Curve Number	I_a (in)
40	3.000	70	.857
41	2.878	71	.817
42	2.762	72	.778
43	2.651	73	.740
44	2.545	74	.703
45	2.444	75	.667
46	2.348	76	.632
47	2.255	77	.597
48	2.167	78	.564
49	2.082	79	.532
50	2.000	80	.500
51	1.922	81	.469
52	1.846	82	.439
53	1.774	83	.410
54	1.704	84	.381
55	1.636	85	.353
56	1.571	86	.326
57	1.509	87	.299
58	1.448	88	.273
59	1.390	89	.247
60	1.333	90	.222
61	1.279	91	.198
62	1.226	92	.174
63	1.175	93	.151
64	1.125	94	.128
65	1.077	95	.105
66	1.030	96	.083
67	.985	97	.062
68	.941	98	.041
69	.899		

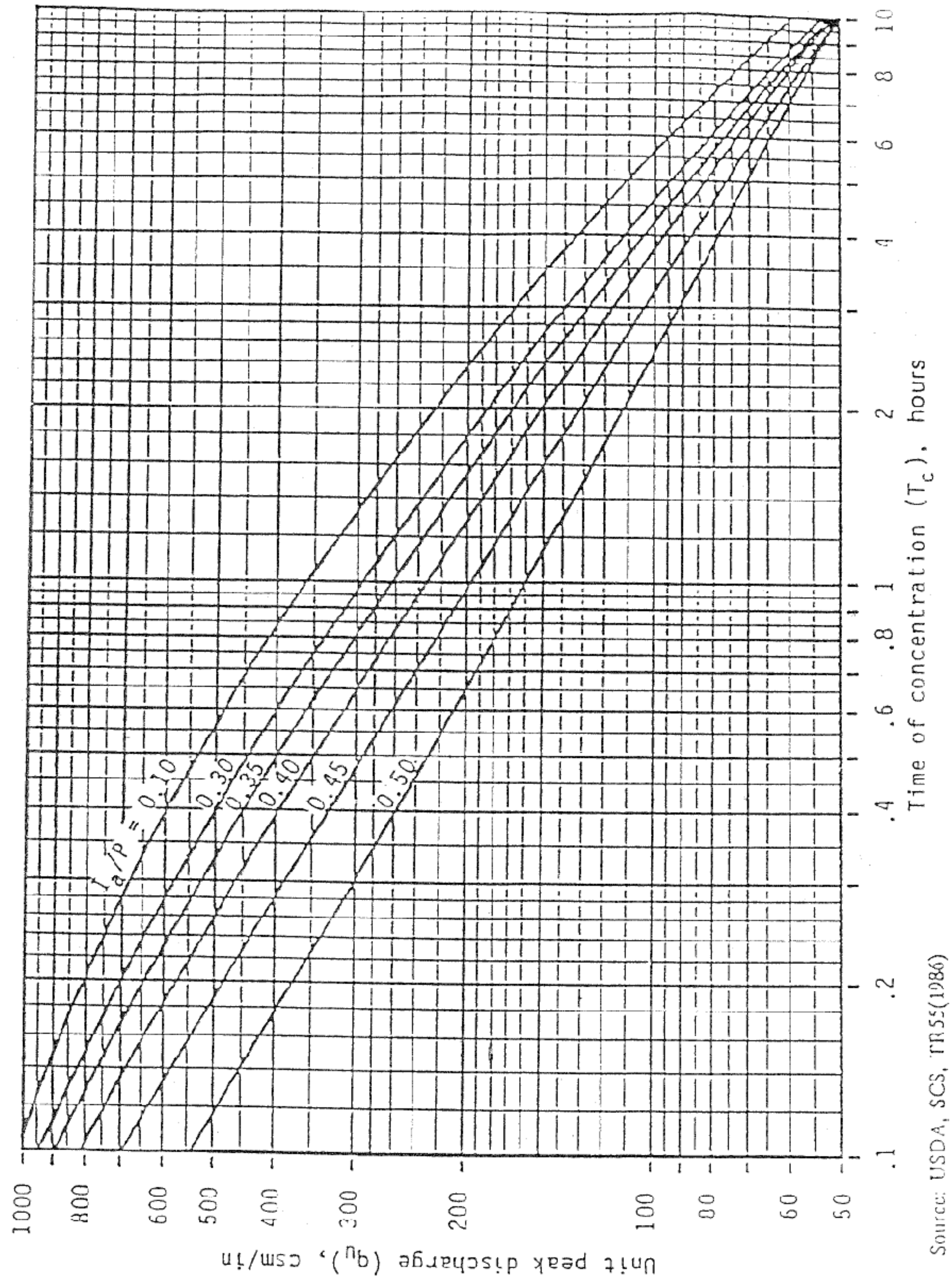

Figure 2-8 SCS Type II Unit Peak Discharge Graph

2.7.3 Limitations

The accuracy of the peak discharge method is subject to specific limitations, including the following.

1. The watershed must be hydrologically homogeneous and describable by a single/composite CN value.
2. The watershed may have only one main stream, or if more than one, the individual branches must have nearly equal time of concentrations.
3. Hydrologic routing cannot be considered.
4. The pond and swamp adjustment factor, F_p, applies only to areas located away from the main flow path.
5. Accuracy is reduced if the ratio I_a/P is outside the range given in Figure 2-7.
6. The weighted CN value must be greater than or equal to 40 and less than or equal to 98.
7. The same procedure should be used to estimate pre- and post-development time of concentration when computing pre- and post-development peak discharge.
8. The watershed time of concentration must be between 0.1 and 10 hours.

2.7.4 Example Problem

Compute the 25-year peak discharge for a 50-acre wooded watershed which will be developed as follows:

1. Forest land - good cover (hydrologic soil group B) = 10 ac.
2. Forest land - good cover (hydrologic soil group C) = 10 ac.
3. Town house residential (hydrologic soil group B) = 20 ac.
4. Industrial development (hydrological soil group C) = 10 ac.

Other data include:

percentage of pond and swamp area = 0.

The hydrologic flow path for this watershed = 1,920 ft.

Segment	Type of Flow	Length	Slope (%)
1	Overland (n = .45)	70 ft.	2.0 %
2	Shallow channel	750 ft.	1.7 %
3	Main channel*	1100 ft.	0.20 %

* For the main channel, n = .025, width = 10 feet, depth = 2 feet, rectangular channel.

Computations

1. Calculate rainfall excess:

The 25-year, 24-hour rainfall for Lincoln, Nebraska is 5.37 inches (see Table 2-7).

Composite weighted runoff coefficient is:

Dev. #	Area	% Total	CN	Composite CN
1	10 ac.	.20	55	11.0
2	10 ac.	.20	70	14.0
3	20 ac.	.40	85	34.0
4	10 ac.	.20	91	18.2
Total	50 ac.	1.00		77.2 use 77

2. Calculate time of concentration (Note: use the method outlined in Appendix 2-C.)

Segment 1 - Travel time from equation 2.C.3 with P_2 = 3.00 in.

$T_t = [0.42\ (0.45 \times 70)^{0.8}] / [(3.00)^{0.5}\ (.02)^{0.4}]$
T_t = 18.3 minutes

Segment 2 - Travel time from equation 2.C.5 and equation 2.C.1

V = 2.7 ft/sec (equation 2.C.5)

T_t = 750 / 60 (2.7) = 4.6 minutes

Segment 3 - Using equation 2.C.6 and equation 2.C.1

$V = (1.49/.025)\ (1.43)^{0.67}\ (.002)^{0.5}$ = 3.4 ft/sec
T_t = 1100 / 60 (3.4) = 5.4 minutes

T_c = 18.3 + 4.6 + 5.4 = 28.3 minutes (.47 hours)

3. Calculate I_a/P

For CN = 77, I_a = .597 (Table 2-13)

I_a/P = (.597 /5.37) = .111
(Note: Use I_a/P = .10 to facilitate use of Figure 2-8.

4. Estimate unit discharge q_u from Figure 2-8 = 550 cfs/mi²/in

5. Calculate peak discharge with F_p = 1 using equation 2.9

From Figure 2-4 (or equation 2.4), Q = 2.9 inches
Q_{25} = 550 (50/640) (2.9) (1) = 125 cfs.

2.7.5 Hydrograph Generation

In addition to estimating the peak discharge, the SCS method can be used to estimate the entire hydrograph. The Soil Conservation Service has developed a tabular hydrograph procedure which can be used to generate the hydrograph for small drainage areas. The tabular hydrograph procedure uses unit discharge hydrographs which have been generated for a series of times of concentrations.

The tables in Appendix 2-A at the end of this chapter give the unit discharges (csm/in) for different times of concentration which are applicable to the City of Lincoln. The values that should be used are those with a travel time equal to zero. The other travel times indicate the unit hydrographs which would result if the hydrographs were routed through a channel system for a length of time equal to the travel time. Thus, using these unit hydrographs would account for the effects of channel routing. Straight line interpolation can be used for time of concentrations and travel times between the values given in the appendix.

2.7.6 Composite Hydrograph

The procedures given in this chapter are for generation of a hydrograph from a homogeneous developed drainage area. For drainage areas which are not homogeneous, hydrographs need to be generated from sub-areas and then routed and combined at a point downstream. To accomplish this, engineers should refer to the procedures outlined by the SCS in the 1986 version of TR-55 available from the National Technical Information Service in Springfield, Virginia or www.usda.nrcs.gov. The catalog number for TR-55, "Urban Hydrology for Small Watersheds," is PB87-101580.

2.7.7 Hydrograph Computation

For the example problem in 2.7.4, calculate the entire hydrograph from the 50 acre development.

Using the chart in Appendix 2-A with a time of concentration of 0.47 hours and $I_a/P = 0.10$, the following hydrograph can be generated (using straight line interpolation between time of concentration of .4 and .5 hours).

The values given in the charts are in csm/in or cubic feet per second per square mile per inch of runoff. Thus, for this example all values from the chart must be multiplied by 0.078 (50 acres/640 acres per square mile), 2.9 inches of runoff, and 1 for the ponding factor - (50/640)(2.9)(1) = 0.23

As an example, from the chart in Appendix 2-A with $T_c = 0.47$ hours and $I_a/P = 0.10$, the unit discharge at time 12.1 hours is 200 csm/in. Thus, the ordinate on the hydrograph for this example would be 200(.23) = 46 cfs. This calculation must be done for all hydrograph values. The results for selected time values are given in Table 2-14.

Table 2-14 Hydrograph Calculation Results for Selected Time Values

*Hydrograph Time (hours)	Unit Discharge (csm/in)	Hydrograph (cfs)
11.0	17	4
11.3	23	5
11.6	33	8
11.9	63	14
12.0	108	25
12.1	200	46
12.2	359	83
12.3	505	116
12.4	544	125
12.5	484	111
12.6	371	85
12.7	273	63
12.8	207	48
13.0	129	30
13.2	91	21
13.4	71	16
13.6	59	14
13.8	52	12
14.0	46	11
14.3	40	9
14.6	36	8
15.0	32	7
15.5	29	7
16.0	26	6

* Note skips in time increments.

2.8 Hydrologic Computer Modeling

2.8.1 Introduction

Hydrologic computer models are in widespread use. They are becoming more “user-friendly”, more capable and flexible, and usually provide “report-ready” output. However, a model’s real utility is in monitoring changes in the watershed or asking “what if” questions. For example, what happens to the 10-year peak discharge as a portion of the watershed becomes urbanized? Or, alternatively, can the peak discharge be reduced substantially with a strategically placed detention pond? Many hydrologic models will allow one to:

- quantify urban runoff (peaks, volumes, and in some cases, water quality),
- obtain design information (channels, pipes, reservoirs, etc.),
- determine the effects of control options (infiltration devices, retention ponds, etc.),
- perform frequency analysis, and
- provide input to economic models.

HEC-HMS (a nonproprietary model written by the U.S. Army Corps of Engineers) has been selected for use in Lincoln by the Public Works & Utility Department and the Lower Platte South NRD.

As you begin to use hydrologic computer models, keep in mind the memorable cliché: "Computers are fast, accurate, and stupid. People are slow, inaccurate, and brilliant. The combination is an opportunity beyond imagination." However, one needs to remain "brilliant" by studying the underlying algorithms these models use. If one knows their limitations, he or she can use computer models wisely.

2.8.2 Concepts and Equations

Modern hydrologic models generally require the user to assemble watershed elements on the computer screen in a link-node structure. That is, nodes represent sub-basins (sub-watersheds), confluences (junctions, manholes, etc.), channels/pipes, and reservoirs. These nodes are "linked" together in an arrangement that depicts how runoff passes through the watershed.

Mathematical algorithms are associated with each node. For example, a sub-basin node will require certain information from the user in order to generate a runoff hydrograph. Rainfall is a necessary input. The user will also be required to input items like area, curve number, slope, etc. With this information, the model uses internal algorithms to compute a runoff hydrograph and sends it to the next downstream element. If this element is a channel/pipe node, other data will be required to route the hydrograph to the next element. Reservoir nodes also perform routing computations. A confluence node combines two or more hydrographs from upstream sub-basins, channels/pipes, and/or reservoirs. The hydrograph(s) continue to move downstream through all of the watershed elements.

SCS procedures are embedded in most hydrologic models. HEC-HMS allow the user to model watersheds with SCS methodology. Therefore, the concepts and equations mentioned previously in this chapter are still appropriate. These include the 24-hour storm, SCS rainfall distributions (like the Type II appropriate for Lincoln), the curve number method for allocating rainfall losses, and the SCS unit hydrograph procedure.

2.8.3 Application

The application of a good hydrologic model is not complicated, particularly if you have a good background in hydrology and a basic understanding of the underlying algorithms used by the model. The step-by-step modeling procedure listed below is typical of most modern hydrologic models. Of course, the sequence of steps taken and the particular data requested are dependent upon the model used and the solution methodology (algorithms) chosen.

The step-by-step modeling procedure is likely to progress as follows:

- Launch the model and name your new file.
- Choose a system of units, give the project a title, and insert project comments.
- Build a watershed schematic (link/node) using the elements provided on the "tool palette."
- Choose a solution methodology (e.g., SCS) for individual watershed elements.
- Input requested data (e.g., rainfall, curve number, etc.) for each watershed element.
- Add any remaining general data (e.g., time step) and run the model.
- Interrogate individual elements from the watershed schematic for output (e.g., hydrographs).
- Evaluate the output data based on sound engineering judgement.
- Use the conclusions to determine estimates to the model for reliable output.

2.8.4 Limitations

Hydrologic models are subject to the same limitations as their underlying algorithms. For example, if SCS modeling procedures are utilized, the precautions and limitations mentioned in section 2.6.4 still apply. The major limitations of the SCS methodology are listed below.

- Curve numbers describe average conditions, particularly with regard to antecedent moisture conditions. Since a watershed or sub-watershed is described by one CN value, it should be delineated (to the extent feasible) such that it is hydrologically homogeneous. (See section 2.7.4 on weighted curve numbers.)
- Initial abstractions are assumed to be 20% of a basin's potential losses.
- Runoff from snowfall or frozen ground cannot be accounted for using SCS procedures.
- SCS procedures account for surface runoff only, not interflow or groundwater contribution.

Since many hydrologic procedures contain empirical parameters, the processes of calibration and verification can be very useful in improving model accuracy. These processes require measured rainfall and runoff data from historical events. Calibration requires that a watershed be modeled using rainfall information from a number of historical storms. Certain empirical parameters are adjusted in the process so that the modeled output matches the measured output. Verification follows calibration. Using completely different historical rainfall information (not the same storms used for calibration), the model is run again with the adjusted empirical parameters to determine the accuracy of the results. If the modeled runoff from these new storms closely matches the measured runoff, the model is assumed to be "verified." The process of calibration and verification is highly desirable and increases confidence in the results of a hydrologic model.

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